MINIATURE 100-kV EXPLOSIVELY DRIVEN PRIME POWER SOURCES BASED ON TRANSVERSE SHOCK-WAVE DEPOLARIZATION OF $Pb(Zr_{0.95}Ti_{0.05})O_3$ FERROELECTRIC CERAMICS

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Abstract

Our previous efforts [1-7] were focused on designing, constructing and investigating miniature shock wave ferroelectric generators (FEGs) based on $Pb(Zr_{0.52}Ti_{0.48})O_3$ (PZT 52/48) poled ferroelectric ceramics (that is widely used in modern technology). In this paper, we extended our efforts to development of FEGs utilizing different type of ferroelectric materials, i.e. $Pb(Zr_{0.95}Ti_{0.05})O_3$ (PZT 95/5). The design of autonomous ultrahigh-voltage FEGs based on transverse explosive shock depolarization of poled PZT 95/5 ferroelectric ceramics was explored and studied. As a result of this work, miniature generators (diameter 38 mm) that are capable of producing output voltage pulses with amplitudes exceeding 120 kV and pulse widths of 3 μs were developed.

I. INTRODUCTION AND BACKGROUND

The development of miniature high voltage autonomous generators is a key part of some modern scientific and engineering projects [1,8,9]. Earlier [2-5] we reported on the development of compact prime power sources utilizing quasi-planar-shock-wave depolarization of $Pb(Zr_{0.52}Ti_{0.48})O_3$ (PZT 52/48) ferroelectrics. Studies of the physical and electrical properties of ferroelectrics compressed by planar shock waves generated with light gas guns and explosively accelerated pellets have been performed since the 1960s and continue until the present time [10-18]. One of the effects associated with the planar-shock-wave compression of poled ferroelectrics is the generation of a high electric voltage at the electrodes of the ferroelectric element due to shock depolarization. Before shock compression, the electric field in the ferroelectric element is equal to zero because of compensation by the surface charge (the bonded charge) of the polarization of the element, $\boldsymbol{P}_0$, obtained during the poling procedure. Planar-shock-wave depolarization releases the surface charge at the electrodes, and correspondingly, a high electric potential is generated across the element.

Because of the large size of the systems used to investigate materials compressed by planar shock waves [10-18] these techniques cannot be used to initiate shock waves in miniature ferroelectric generators (FEGs). For longitudinal [2, 3] and transverse [4] (shock wave propagates along and across the polarization vector $\boldsymbol{P}_0$, correspondingly) FEGs we developed compact generators of quasi-planar shock waves utilizing explosively accelerated metallic impactor (flyer plate). These FEGs routinely produce output voltages exceeding 40 kV [2-4].

For certain scientific and engineering projects it is important to develop miniature prime power sources that reliably generate ultrahigh (up to 100 kV) output voltages. We work on this problem since the beginning of the 2000s. In accordance with our previous concept, the device contains two stages: a prime power stage and a pulse-transforming stage. We experimentally proved this concept earlier [19,20]. The prime power was provided by shock-wave FEG [2-4] or shock-wave ferromagnetic generators (FMG) [21], and a vector inversion generator (VIG) [22] was used as a pulse-transforming stage. These FMG-VIG and FEG-VIG systems were capable of producing high voltage pulses with amplitudes up to 92 kV [19]. However, there are several disadvantages in two-stage ultrahigh-voltage generators, i.e. their complexity, large size and large weight.

Our second concept of FEG-based autonomous ultrahigh-voltage systems was a single-stage FEG that is capable of producing ultrahigh-voltage pulses without a

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14. ABSTRACT
Our previous efforts [1-7] were focused on designing, constructing and investigating miniature shock wave ferroelectric generators (FEGs) based on Pb(Zr0.52Ti0.48)O3 (PZT 52/48) poled ferroelectric ceramics (that is widely used in modern technology). In this paper, we extended our efforts to development of FEGs utilizing different type of ferroelectric materials, i.e. Pb(Zr0.95Ti0.05)O3 (PZT 95/5). The design of autonomous ultrahigh-voltage FEGs based on transverse explosive shock depolarization of poled PZT 95/5 ferroelectric ceramics was explored and studied. As a result of this work, miniature generators (diameter 38 mm) that are capable of producing output voltage pulses with amplitudes exceeding 120 kV and pulse widths of 3 Ýs were developed.

15. SUBJECT TERMS

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pulse-transforming stage or any other power-conditioning stage [6]. The starting point for this research and development work [6] was results we obtained earlier with planar-shock-wave FEGs [2-4]. The problem with these FEGs [2-4] is that the presence of a flyer plate in the generators significantly increases the amount of high explosives (HE), the size and weight of the generators, and becomes a limitation factor developing miniature ultrahigh voltage prime power sources. In [5], we reported on the detection longitudinal and transverse shock depolarization effects in PZT 52/48 ferroelectrics induced by cylindrical radially-expanding shock waves generated directly from detonating the high explosives and successful utilization of these effects for the construction of axial FEGs.

In [6] we further developed our design approaches. As a result of these efforts [6], we developed and studied a series of ultrahigh voltage FEGs utilizing transverse shock depolarization of PZT 52/48 ferroelectrics. These generators (patented by Loki Incorporated [7]) contain no moving metallic parts and are capable of producing output voltage pulses with amplitudes exceeding 125 kV [6].

In the present paper, we report on results of development of miniature FEGs utilizing PZT 95/5 ferroelectric ceramic elements. These generators with volume less 90 cm^3 reliably generate output voltages exceeding 120 kV.

II. FERROELECTRIC MATERIALS

Poled PZT 95/5 ceramic is under intensive shock compression studies since late 1960s [14] and until now [19]. A new technology for the production of high-quality lead zirconate titanate $Pb(Zr_{0.95}Ti_{0.05})O_3$ ferroelectric ceramics for explosive pulsed power applications has been under development by TRS Technologies for the past few years [23-25]. Their PZT 95/5 ceramics was previously tested by HEM Technologies [24] and KTECH Corp. [23].

Cylindrical PZT 95/5 ceramic ferroelectric elements (diameter D = 19.0 mm and thickness l = 23.1 mm) were prepared by TRS Technologies Inc. [25]. Silver electrodes were deposited on both planes of each PZT 95/5 cylinder by the manufacturer. Ferroelectric elements were poled across the thickness to their remnant polarization by the manufacturer.

A photograph of one of the PZT 95/5 ferroelectric elements used in this work is shown in Fig. 1. The parameters of the PZT 95/5 feroelectrics were: theoretical density (TD) 8.00 g/cm^3, typical density 95-97 %TD, the dielectric constant and loss (unpoled) 410/2.00%, the dielectric constant and loss (poled) 350/1.97%, the dielectric strength ~ >8.0 MV/m, maximum remnant polarization 0.39 C/m^2, typical remnant polarization 0.32 C/m^2, piezoelectrtic coefficient d_{33} and d_{31} 68 pC/N/-16 pC/N, voltage coefficient g_{33} and g_{31} = 26.28/-5.99 x10^{-3} Vm/N, electromechanical coupling coefficient k_p, k_{31}, and k_t 18.2%/11.1%/46.0%, elastic compliance S_{11E} and S_{12E} 7.68/-1.97x10^{-12} m^2/N, acoustic velocity and Poissons' ratio 4194 m/s/0.2572, thickness mode N_t and Q_m = 2105.

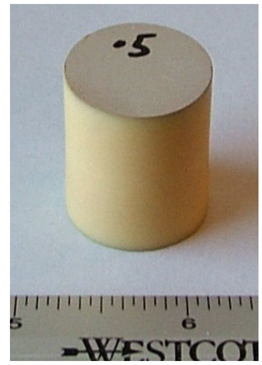

Figure 1. PZT 95/5 ferroelectric element.

III. FEG DESIGN

We used the design of the transverse FEG we developed earlier for PZT 52/48 ferroelectrics [6,7] as a basis for this research and development work. A schematic diagram of the transverse shock wave FEG is shown in Fig. 2. The FEG contained two parts: a detonation chamber and a ferroelectric element incorporated in the plastic body. The ferroelectric element was encapsulated with epoxy as electrical insulating material. The distance between the top of the plastic body and the ferroelectric unit varied from 15 to 30 mm. The FEGs (Fig. 2) did not contain moving metallic parts. The shock wave in the ferroelectric element was generated by detonating the high explosives. The HE was in direct contact with the top of the plastic body. We used desensitized RDX high explosives (detonation velocity 8.04 km/s and theoretical dynamic pressure at the shock front 36.7 GPa) and RISI RP-501 detonators.

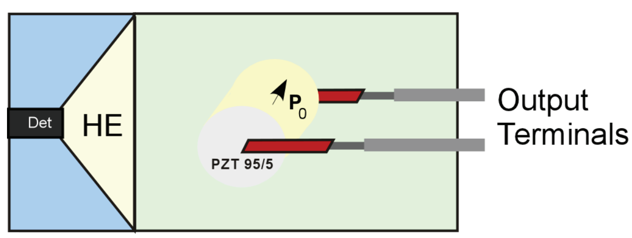

Figure 2. Schematic diagram of an explosively driven FEG utilizing transverse shock wave depolatrization of PZT 95/5 ferroelectrics. $\boldsymbol{P}_0$ is the polarization vector.

The diameter of the FEGs was 38 mm. The detonation chamber cone angle was 60°. The mass of RDX was 10.4±0.7 g.

IV. EXPERIMENTS

A schematic diagram of the experimental setup and measuring circuit for studies of explosively driven FEGs are shown in Fig. 3. The experiments were conducted in the facilities of the Energetic Materials Research Laboratory at the Missouri University of Science and Technology, Rolla, MO. The FEGs were placed within the blast chamber. The FEG output voltage was monitored with a North Star PVM-5 high voltage probe (resistance 400 MΩ, capacitance 12 pF) placed outside the blast chamber and connected to the output terminals of the FEG. Other experimental details are described elsewhere [2-6, 19].

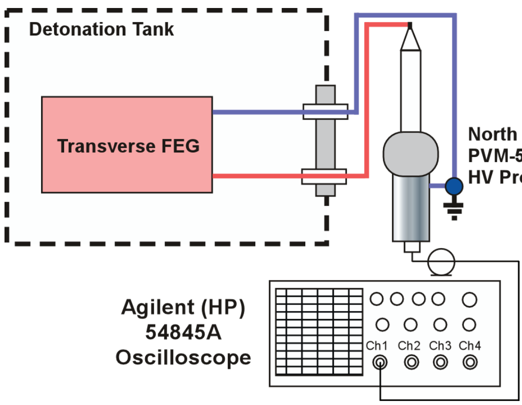

Figure 3. Schematic diagrams of experimental setup and measuring circuit for investigations of explosively driven FEGs.

V. RESULTS AND DISCUSSION

The operation of the FEG (Fig. 2) was as following. After ignition of the detonator the detonation wave propagated in the HE charge toward to the top of the plastic body. The spherical shock wave front reached the PZT 95/5 element and propagated through it. As a result of shock depolarization the surface electric charge was released at the electrodes of the PZT 95/5 element and an output voltage was generated at the output terminals of the FEG. The amplitude of the voltage pulse depended on the degree of the depolarization of the PZT 95/5 ferroelectrics due to the shock compression.

A typical waveform of the output voltage produced by an FEG containing a single PZT 95/5 cylinder (D = 19.0 mm and l = 23.1 mm) is shown in Fig. 4. The amplitude of the voltage pulse was $U(t)_{max}$ = 121.0 kV with rise time τ = 2.2 μs. The amplitude of the output voltage averaged over seven experiments of this series was U_g = 121±4 kV.

The FEG is a capacitive-type prime power source. The output energy, W, produced by an FEG is directly proportional to the square of the amplitude of the FEG output voltage, U_{out}, and to the capacitance of the ferroelectric element, C_G:

$$W = C_G \cdot \left(U_{out}^2\right)/2\,. \tag{1}$$

The C_G can be determined from the geometrical dimensions and the dielectric properties of the ferroelectric element:

$$C_G = \left(\pi \cdot \varepsilon \cdot \varepsilon_0 \cdot D^2 \cdot l\right)/4\,, \tag{2}$$

where ε_0 is the vacuum dielectric constant, ε is the relative dielectric constant of the ferroelectric material, D is the diameter of the PZT 95/5 cylinder, and l is the cylinder length.

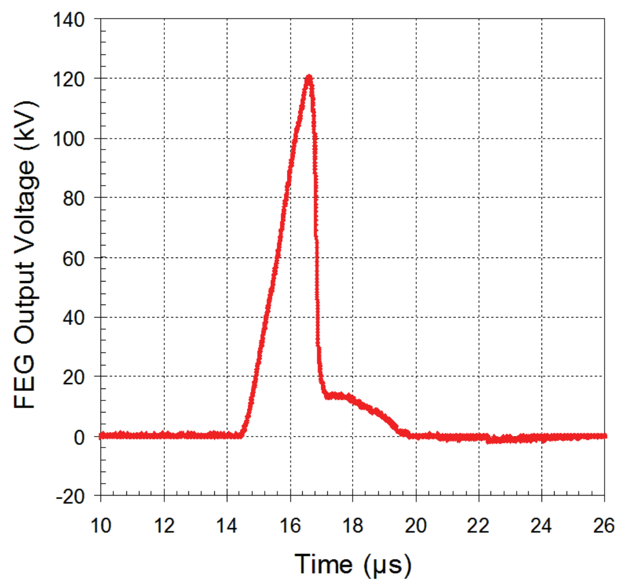

Figure 4. A typical waveform of the output voltage pulse produced by an FEG (38-mm diameter containing PZT 95/5 cylindrical element (D = 19.0 mm and l = 23.1 mm).

Accurate measurement of the relative dielectric constant, ε, of shocked ferroelectrics is a very difficult task. To calculate the energy generated by a shocked ferroelectric element in the open circuit mode, we used the value of ε for unpoled 95/5 ferroelectrics provided by the manufacturer, 350. Substitution of these parameters into Eqs. 1 and 2 gives us an estimate of the output energy of the FEG, W = 0.42±0.04 J.

VI. SUMMARY

Explosively-driven autonomous ultrahigh-voltage prime power sources utilizing transverse shock wave depolarization of $Pb(Zr_{0.95}Ti_{0.05})O_3$ ferroelectric ceramics were designed, constructed and experimentally studied. These miniature generators (diameter 38 mm) patented by Loki Incorporated [7] are capable of producing output voltages exceeding 120 kV with pulse widths of 3 μs.

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